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Compressive Strength Models of Repaired Concrete Structures

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Abstract. Application of confinement as repairing technique can improve the strength and ductility of concrete significantly. This paper compares the existing models of repaired concrete, and describes the differences between these models. Over recent years, a great number of studies have been done to develop the models to define the stress-strain behaviour of repaired structures. The considered variables are the cross-sectional area, types of confinement, types of materials used and type of the strength models. Subsequently, the limitations were discussed and significant conclusions on the strength and weakness of each existing models were highlighted. This paper presented the state of the art design strength models available for repaired concrete structures and indicated a direction for future development.

INTRODUCTION

Recently, external confinement has been used for repairing reinforced concrete (RC) structure as it can enhance the axial load carrying capacity of damaged concrete. The factors of damages can be as follows [1,2]:

- Seismic loads- The failure occurs when the seismic loads are higher than seismic resistivity.
- Environmental effects- The variance in temperature or freeze-thaw effects resulting in a change of porosity of concrete that leads to the disintegration of concrete structures.
- Corrosion- Effects from carbonation, exposure to water or chlorides, and high levels of humidity.
- Concrete scaling- Deficient of concrete bond or large size of aggregates that cause the mixture of the concrete shows a discontinuity region.
- Increase in service loads- the change in the use of existing structure will cause a rise in service loads and consequently, the failure occurs.

The different approach in applying repairing techniques depends on the type of damage and the geometry of the structure. Therefore, in literature, there are several compressive strength models were developed to define the strength and ductility of the confinement structures. In order to explain the behaviour of repaired concrete, extensively studies on experimental and analytical are required. Mainly, the effectiveness of confinement is affected by: i) the type of repair material used; ii) cross-sectional area; and iii) type of confinement considers. Generally, the type of material used are Fiber Reinforced Polymer (FRP), modified FRP, mortar, steel jacketing and other related material. Subsequently, the typical cross-section adopt was circular, square or rectangular area. Generally, there are two categories of confinement viz, active and passive confinement. Active confinement refers to the formation of lateral confining pressure prior to the application of axial load. Whilst, passive confinement is the lateral confining pressure was initiated subsequently with the acts of the loading. The lateral pressure will influence the behaviour of dilations and deformation of confined concrete structures. Therefore, it is essentials to understand the response of

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concrete members that being confined. Most of the previous studies reported in literature emphasised only on passively stress-strain models even though, it was reported that this method was ineffective due to the confining pressure developed when concrete is starting to dilate upon loading [3-7].

Wu et al. [8], reported the behaviour of repaired concrete using CFRP by variations level of damage degree, compressive strength of concrete and lateral confinement pressure. Rabehi et al. [9], proposed an analytical model for compressive strength of repaired concrete columns according to the two techniques which are increasing in cross-section area and wrapping by using FRP. While, Achillopoulou and Karabinis [10], defined the numerical model by considering the influence of casting imperfections for repaired structure.

MECHANISM OF CONFINEMENT

Effective Confinement Area

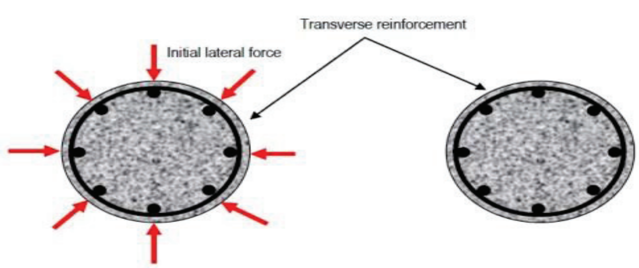
Practically, confinement effects can enhance load carrying capacity of the damaged structure. Confinement consists of wrapping material, such as FRP, ferrocement, steel, and concrete. The use of concrete confinement can improve lateral pressure of structure as a result of an increase in ductility and load capacity. Confinement for square and rectangular area is inefficient rather than circular section. This is explained in Figure 1., where the shaded region shows an effective area of confining pressure[11].

(a) (b) (c)

FIGURE 1. Effective confinement area, (a) circular area, (b) square area, (c) rectangular area [11]

Active and Passive Confinement

There are two types of confinement. That is active and passive types of confinement. The behavior of these confinements is different in terms of the lateral confining pressure exerted on it. Active confinement allowed for multiaxial compression while passive confinement produces a small confining stress [12]. Figure 2. shows the distribution lateral force of active and passive confinement to prestress the concrete at the initial stage prior to loading [13].



(a) (b)

FIGURE 2. (a) Active, (b) Passive lateral pressure formations [13]

REVIEW OF CONFINED MODELS

Early models present passively confinement of concrete for column repairs, peculiarly for uniform plain circular columns or noncircular cross-section area. The studies also reported that the confined concrete performs differently based on the type of materials used. Therefore, there are various design models was developed in order to anticipate the compressive strength behaviour.

There consist of two parts of strength models which is design-oriented and analysis-oriented models [14,15]. Design-oriented models is developed through mathematical analysis that was calibrated from compression test results and produce closed form equation. Meanwhile, for analysis-oriented models are developed based on increasing iterative numerical procedure. In design-oriented models, the expression models as follows:

$$\frac{f_{cc}}{f_{cd}}=1+k\ \frac{f_l}{f_{cd}} \tag{1}$$

where, f_{cc}= compressive strength of confined concrete; f_{cd}= compressive strength unconfined concrete; k= confinement effectiveness coefficient and f_l= lateral confining pressure. Thus, for lateral confining pressure, generally it considers the value of maximum transverse stresses occurs at the fracture of jackets;

$$f_l=\frac{2t_{frp}}{d}\ f_{frp} \tag{2}$$

where, f_{frp} represent tensile strength of the jacket; t is total thickness of jacket layers, and d is diameter of confined column. The value of k is depend on $\frac{f_l}{f_{co}}$ or f_l. From literature review, the model proposed by Wu et al. [8], represent the compressive strength for circular column under concentric loading such as in Eq. (3). The damage degree (δ) of concrete was taken into consideration in the expression as it influencing the strength obtain.

$$\frac{f_{cc}}{f_{co}}=1+3.96\left(\frac{f_l}{f_{co}}\right)^{1.13}-0.988 \tag{3}$$

Besides, Rabehi et al.[9] developed compressive strength model into two parts which are by wrapping using composites FRP and enlarge the concrete sections. The two types of composite FRP were used which is, carbon fiber reinforced polymer (CFRP) and glass fiber reinforced polymer (GFRP). The full expression was shown in Eq. (4) and (5). Whereas the two types of concrete were used in an enlargement cross-section area that is ordinary concrete (OC) and ultra high- performance fiber reinforced concrete (UHPFRC). The ultimate strength for section enlargement given by Eq. (6) and (7) respectively.

Specimens repaired with CFRP;

$$\frac{f_{cc}}{f_{cd}}=1+2\ \frac{f_l}{f_{cd}} \tag{4}$$

Specimens repaired with GFRP;

$$\frac{f_{cc}}{f_{cd}}=1+4.2\ \frac{f_l}{f_{cd}} \tag{5}$$

Specimens repaired with UHPFRC;

$$\frac{f_{cc}}{f_{cd}}=1+2.5\ \frac{f_l}{f_{cd}} \tag{6}$$

Specimens repaired with OC fiber;

$$\frac{f_{cc}}{f_{cd}}=1+1.8\ \frac{f_l}{f_{cd}} \tag{7}$$

The entire stress-strain relationship was not depicted in this paper, and a portion of the models gave an expression just for ultimate strength and disregard of ultimate strain. These points of interest are altogether highlighted in Table 1. Despite that, Wu *et al.*[8] figure out the ultimate strain of damaged elements:

$$\frac{\varepsilon_{cu}'}{\varepsilon_{cu}} = \left(1 - 0.3\left(\frac{f_{co}}{f_{30}}\right)^{2.82} \delta^{0.67}\right) + 0.54\delta \tag{8}$$

which ε_{cu}' is the ultimate strain of damaged concrete; ε_{cu} is the ultimate strain of undamaged concrete; f_{co} peak stress of undamaged concrete; f_{30} strength of concrete grade C30; and δ is the damage degree of concrete. Besides that, Achillopoulou and Karabinis [10] define ultimate strain as:

$$\frac{\varepsilon'_{ccr}}{\varepsilon_{cu}} = (\mathrm{c}+\mathrm{d})\left[\,1 + \frac{\left(\frac{0.85\, d_v \varepsilon_{ccr}}{10000}\right)^{2/3}}{\varepsilon_{cu}}\right] \tag{9}$$

where c, d: the calibration factors ; ε'_{ccr} is the axial yield strain of repaired concrete ; ε_{cu} axial yield strain of unconfined concrete ; ε_{ccr} axial yield strength of confined concrete; d_v is the volumetric index. The volumetric index defined as the combination between section index (d_s), and axial index (d_a) which is;

$$d_v = 1 - \left[\left(1 - \frac{f_1}{f_{nom}}\right)\left(1 - \frac{h_1}{h_{nom}}\right)\right] \tag{10}$$

f_1 indicate damage at cross-section area; f_{nom} is the nominal cross-section area; h_1 is damaged expansion in vertical directions; and h_{im} the specimens height of the existing models. The summary of existing models according to the ultimate strength, ultimate strain and lateral pressure were tabulated in Table 1.

COMPARISON OF EXISTING MODELS

Each model has reviewed for the type of i) cross-sectional area; ii) confinement; iii) strength model and iv) materials used. The models by Wu et al.[8] and Rabehi et al.[9] studies on plain circular concrete cylinders indicate design-oriented model for developing compressive strength of confined concrete. On the contrary, Achillopoulou and Karabinis [10] cast on rectangular RC columns and implement analysis-oriented models for develop strength model. All of the existing models consider passive- typed of confinement. The limitations of these models describe the columns classification and loading scheme used by the researchers. Wu et al.[8] and Rabehi et al.[9] classify their specimens as short columns and used pre-damaged level as loading behaviour. Wu et al.[8], claims the confinement layer influencing the performance of the repaired structures. The thicker of FRP wrapping will reduce the damage of concrete core. This is was due to the partially disintegrated and existing cracking during damaging concrete cause less explosion of concrete at FRP rupture. Conversely, Rabehi et al.[9] found the type of composites materials used will affect of confined concrete in gaining strength. Achillopoulou and Karabinis [10], reported that higher confinement ratio will increase the strain response. The existing models considerations are presented in Table 2.

TABLE 1. Summary of existing models

	Ultimate axial strength of repaired concrete (MPa)	**Lateral confining pressure, f_l (MPa)**	**Ultimate strain of repaired concrete (MPa)**
Wu *et al*[8]	$\frac{f_{cc}}{f_{co}}=1+3.96\left(\frac{f_l}{f_{co}}\right)^{1.13}-0.985$	$f_l=\frac{2t_{frp}}{d}f_{frp}$	$\frac{\varepsilon_{cu}'}{\varepsilon_{cu}}=\left(1-0.3\left(\frac{f_{co}}{f_{30}}\right)^{2.82}\delta^{0.67}\right)+0.54\delta$
Rabehi *et al.*[9]	i) Repaired concrete by using FRP: -Specimens repaired with CFRP; $\frac{f_{cc}}{f_{cd}}=1+2\frac{f_l}{f_{cd}}$ -Specimens repaired with GFRP; $\frac{f_{cc}}{f_{cd}}=1+4.2\frac{f_l}{f_{cd}}$	$f_l=\frac{2t_{frp}}{d}f_{frp}$	N /A
	ii) Repaired by increased concrete section: -Specimens repaired with UHPFRC; $\frac{f_{cc}}{f_{cd}}=1+2.5\frac{f_l}{f_{cd}}$ -Specimens repaired with OC fiber; $\frac{f_{cc}}{f_{cd}}=1+1.8\frac{f_l}{f_{cd}}$	$f_l=\frac{2t}{d}(0.6+0.06f_{c28})$	N/A
Achillopoulou and Karabinis [10]	$\frac{f_{cdm}}{f_{co}}=a+b^*\left(\frac{f_{cc}}{d_s}\right)^{3/4}$ $d_h \leq 0.40$ and $d_v \leq 0.55$ **a* and *b* denotes correlation coefficients	N/A	$\frac{\varepsilon'_{ccr}}{\varepsilon_{cu}}=(c+d)\left[1+\frac{\left(\frac{0.85\,d_V\varepsilon_{ccr}}{10000}\right)^{2/3}}{\varepsilon_{cu}}\right]$

TABLE 2. Existing Models Consideration

Researcher (s)	Cross-sectional area	Active/ Passive confinement	Type of materials used	Type of models	Limitations	Remarks
Wu *et al.*[8]	Concrete cylinders	Passive	CFRP	Design-oriented	-L_{ex} / h < 10 -Pre-damaged level ranging from 0% until ultimate strength for ascending branch -50% to 95% for decending branch	When damage degree is less that 0.2, confinement does not affect the initial elastic modulus. The confinement will effect with an increase in damage degrees.
Rabehi *et al.*[9]	Plain circular concrete	Passive	UHPFRC, OC, and FRP (GFRP, CFRP)	Design-oriented	-L_{ex} / h < 10 -Damage degree up to 70% of ultimate strength	The specimens repaired by UHPFRC is more effective than repaired by increasing section with OC.
Achillopoulou and Karabinis [10]	Rectangular reinforced concrete columns	Passive	Fiber reinforced mortar	Analysis-oriented	-Columns scale ratio (1:2) -Axial loading	Casting deficiencies affects the behaviour of the repaired specimens

CONCLUSIONS

The present study analysed and compared several compressive strength models for repaired concrete. this paper has presented the ultimate compressive strength, lateral confining pressures, and ultimate strain of existing models. based on the observations, the past studies have considered variables such as damage degree, confining pressures, and different type of confining materials in their research. it can be concluded that strength of repairing structures will increase despite of any damage degree. furthermore, the different results will be obtained depending on the type of materials used in repaired concrete structures. as far as the authors are aware, there is no work carried out on active typed confinement. therefore, it is recommended for defined the behaviour of repaired models by considering active confinements for future directions.

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